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- (54) **METHOD AND SYSTEM FOR CONTROLLING A TUNING FACTOR DUE TO SENSOR REPLACEMENT FOR CLOSED-LOOP CONTROLLER IN AN ARTIFICIAL PANCREAS**
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(58) **Field of Classification Search**

None

See application file for complete search history.

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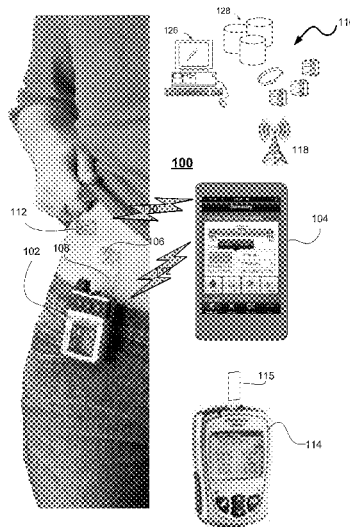
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(57) **ABSTRACT**

Described and illustrated is a system for management of diabetes that includes an infusion pump, glucose sensor and controller with a method programmed in the controller. The infusion pump is configured to deliver insulin. The glucose sensor senses glucose levels in the subject and provide output signals representative of the glucose levels in the subject. The controller is programmed receives signals from at least one of the glucose sensor and the pump and configured to issue signals to the pump to deliver an amount of insulin determined by a feedback controller that utilizes a model predictive control based on desired glucose levels, insulin amount delivered and measured glucose levels of the subject. The controller is also configured to deliver insulin using a tuning factor (R) for a model predictive controller in the microcontroller as a conservative setting otherwise the system maintains a current tuning factor (R) for the controller.

15 Claims, 4 Drawing Sheets



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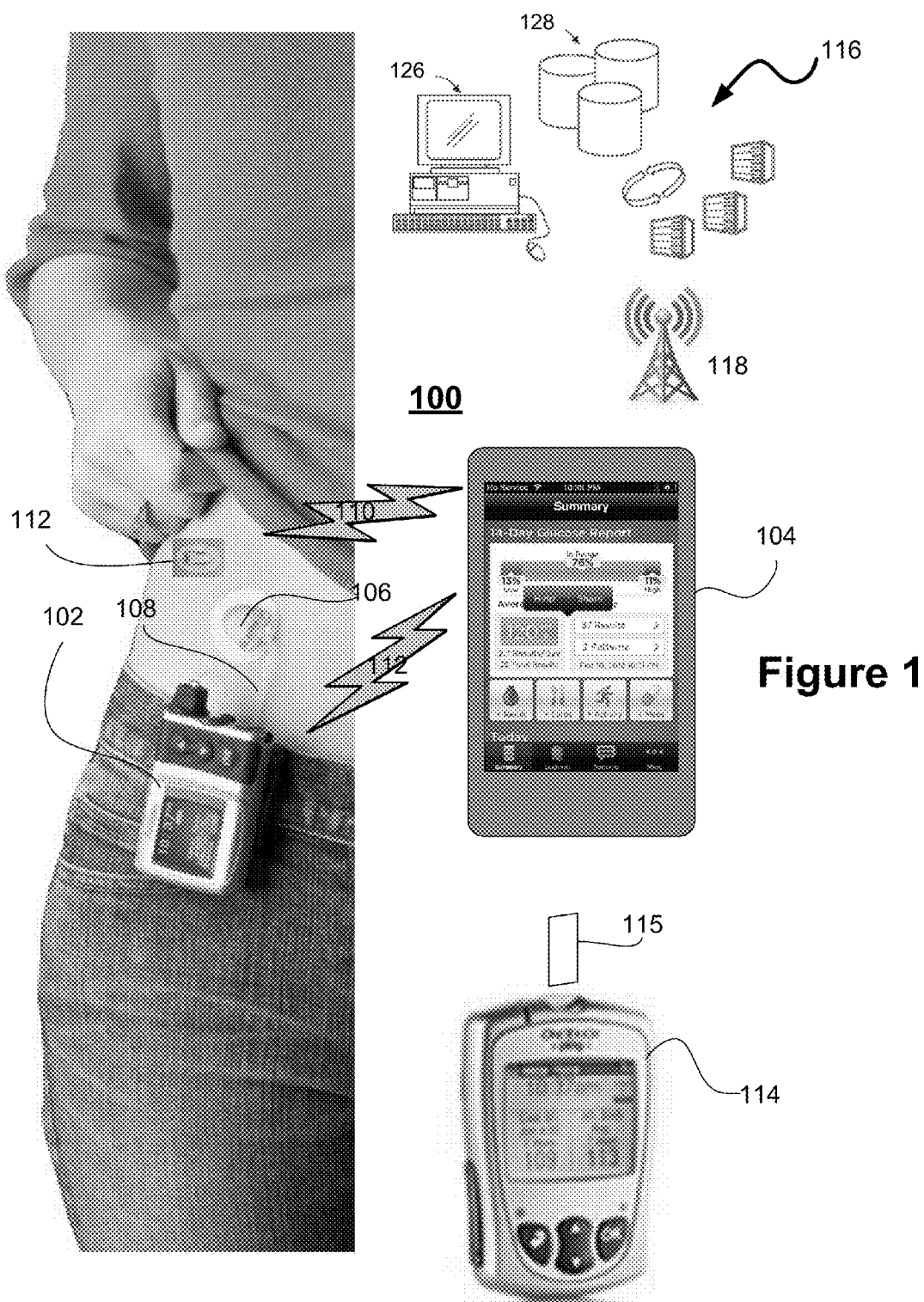
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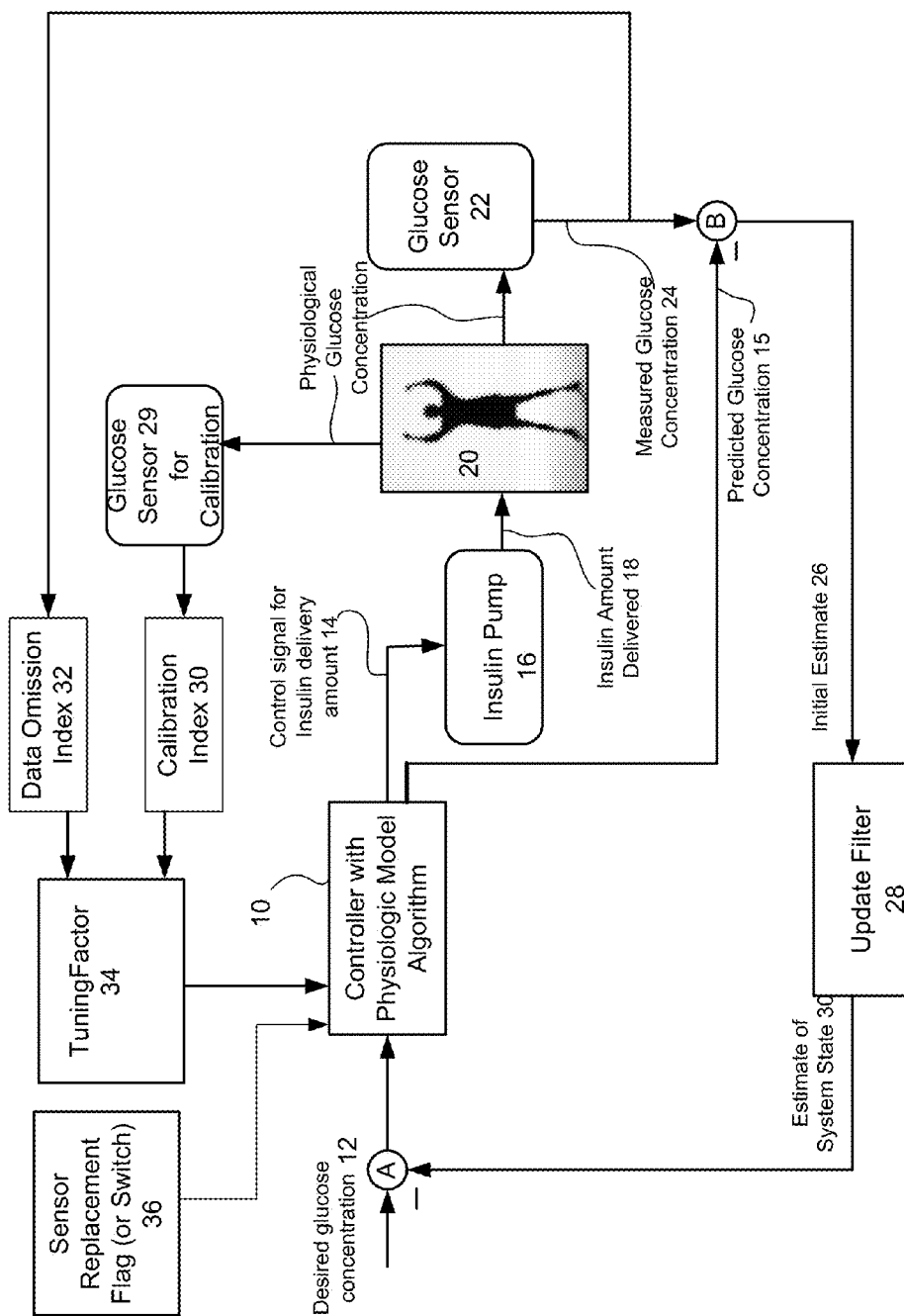
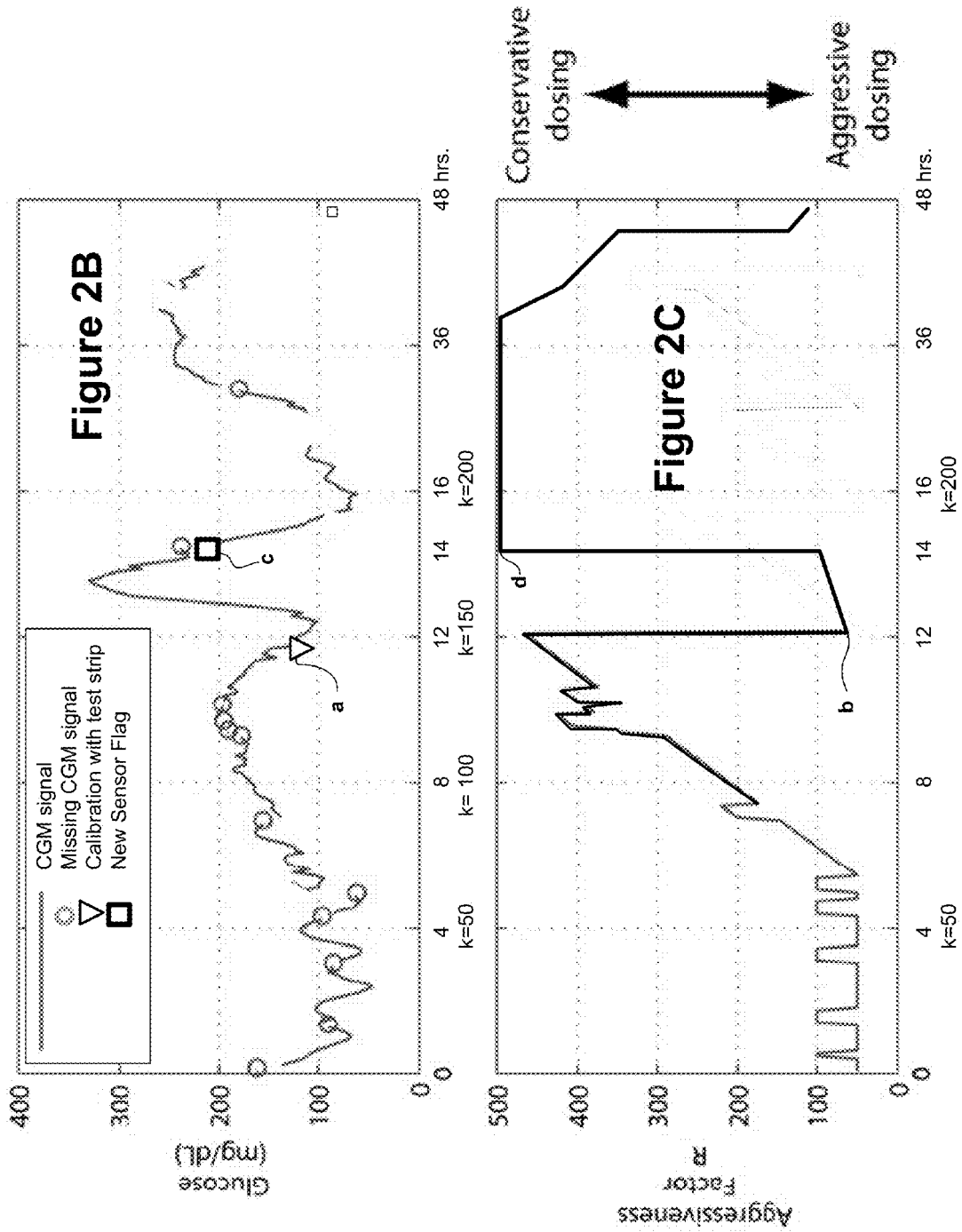
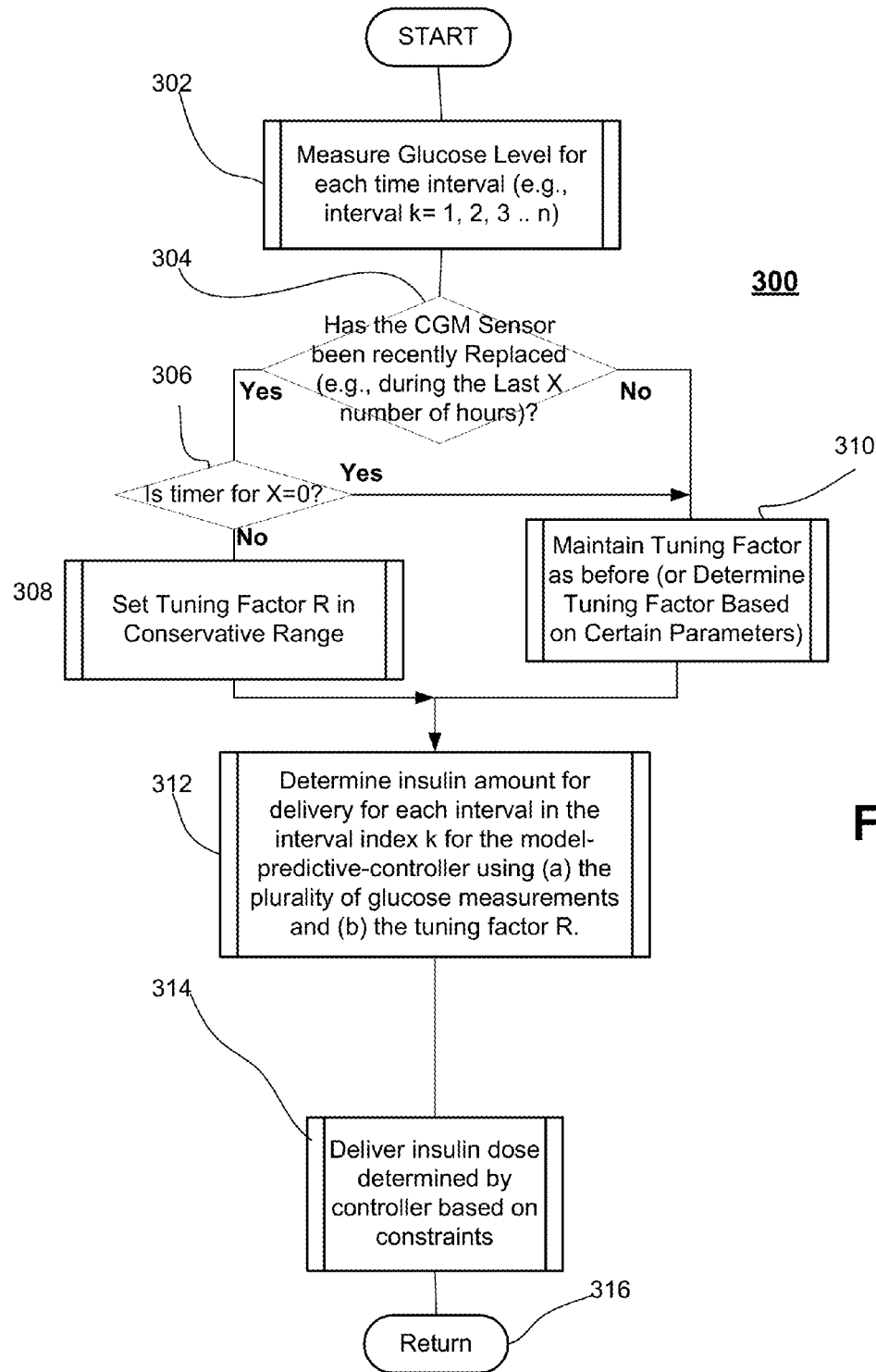


Figure 2A



**Figure 3**

METHOD AND SYSTEM FOR CONTROLLING A TUNING FACTOR DUE TO SENSOR REPLACEMENT FOR CLOSED-LOOP CONTROLLER IN AN ARTIFICIAL PANCREAS

BACKGROUND

Diabetes mellitus is a chronic metabolic disorder caused by an inability of the pancreas to produce sufficient amounts of the hormone insulin, resulting in the decreased ability of the body to metabolize glucose. This failure leads to hyperglycemia, i.e. the presence of an excessive amount of glucose in the blood plasma. Persistent hyperglycemia and/or hypoinsulinemia has been associated with a variety of serious symptoms and life threatening long term complications such as dehydration, ketoacidosis, diabetic coma, cardiovascular diseases, chronic renal failure, retinal damage and nerve damages with the risk of amputation of extremities. Because restoration of endogenous insulin production is not yet possible, a permanent therapy is necessary which provides constant glycemic control in order to always maintain the level of blood glucose within normal limits. Such glycemic control is achieved by regularly supplying external insulin to the body of the patient to thereby reduce the elevated levels of blood glucose.

External biologic such as insulin was commonly administered by means of multiple daily injections of a mixture of rapid and intermediate acting drugs via a hypodermic syringe. It has been found that the degree of glycemic control achievable in this way is suboptimal because the delivery is unlike physiological hormone production, according to which hormone enters the bloodstream at a lower rate and over a more extended period of time. Improved glycemic control may be achieved by the so-called intensive hormone therapy which is based on multiple daily injections, including one or two injections per day of a long acting hormone for providing basal hormone and additional injections of rapidly acting hormone before each meal in an amount proportional to the size of the meal. Although traditional syringes have at least partly been replaced by insulin pens, the frequent injections are nevertheless very inconvenient for the patient, particularly those who are incapable of reliably self-administering injections.

Substantial improvements in diabetes therapy have been achieved by the development of the drug delivery device, relieving the patient of the need for syringes or drug pens and the administration of multiple daily injections. The drug delivery device allows for the delivery of drug in a manner that bears greater similarity to the naturally occurring physiological processes and can be controlled to follow standard or individually modified protocols to give the patient better glycemic control.

In addition, delivery directly into the intraperitoneal space or intravenously can be achieved by drug delivery devices. Drug delivery devices can be constructed as an implantable device for subcutaneous arrangement or can be constructed as an external device with an infusion set for subcutaneous infusion to the patient via the transcutaneous insertion of a catheter, cannula or a transdermal drug transport such as through a patch. External drug delivery devices are mounted on clothing, hidden beneath or inside clothing, or mounted on the body and are generally controlled via a user interface built-in to the device or on a separate remote device.

Blood or interstitial glucose monitoring is required to achieve acceptable glycemic control. For example, delivery of suitable amounts of insulin by the drug delivery device

requires that the patient frequently determines his or her blood glucose level and manually input this value into a user interface for the external pumps, which then calculates a suitable modification to the default or currently in-use insulin delivery protocol, i.e., dosage and timing, and subsequently communicates with the drug delivery device to adjust its operation accordingly. The determination of blood glucose concentration is typically performed by means of an episodic measuring device such as a hand-held electronic meter which receives blood samples via enzyme-based test strips and calculates the blood glucose value based on the enzymatic reaction.

Continuous glucose monitoring (CGM) has also been utilized over the last twenty years with drug delivery devices to allow for closed loop control of the insulin(s) being infused into the diabetic patients. To allow for closed-loop control of the infused insulins, proportional-integral-derivative ("PID") controllers have been utilized with mathematical model of the metabolic interactions between glucose and insulin in a person. The PID controllers can be tuned based on simple rules of the metabolic models. However, when the PID controllers are tuned or configured to aggressively regulate the blood glucose levels of a subject, overshooting of the set level can occur, which is often followed by oscillations, which is highly undesirable in the context of regulation of blood glucose. Alternative controllers were investigated. It was determined that a model predictive controller ("MPC") used in the petrochemical industries where processes involved large time delays and system responses, was the most suitable for the complex interplay between insulin, glucagon, and blood glucose. The MPC controller has been demonstrated to be more robust than PID because MPC considers the near future effects of control changes and constraints in determining the output of the MPC whereas PID typically involves only past outputs in determining future changes. Constraints can be implemented in the MPC controller such that MPC prevents the system from running away when the limit has already been reached. Another benefit of MPC controllers is that the model in the MPC can, in some cases, theoretically compensate for dynamic system changes whereas a feedback control, such as PID control, such dynamic compensation would not be possible.

MPC can be viewed therefore as a combination of feedback and feed forward control. MPC, however, typically requires a metabolic model to mimic as closely as possible the interaction between insulin and glucose in a biological system. As such, due to person-to-person biological variations, MPC models continue to be further refined and developed presently. As informational background on MPC relating to details of the MPC controllers, variations on the MPC, and mathematical models representing the complex interaction of glucose and insulin, all of which are shown and described in the following documents:

U.S. Pat. No. 7,060,059;

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All articles or documents cited in this application are hereby incorporated by reference into this application as if fully set forth herein.

SUMMARY OF THE DISCLOSURE

Applicants have devised a technique that allows for the tuning of the model predictive control such that inaccuracies inherent in a continuous glucose sensor can be qualitatively compensated for in the model predictive controller that is implemented in the microcontroller of our system. In particular, a method is provided to control an infusion pump with a micro controller to control the pump and receive data from at least one glucose sensor. The method can be achieved by: measuring glucose level in the subject from the glucose sensor to provide at least one glucose measurement in each time interval in a series of discrete time interval index ("k"); determining whether the glucose sensor has been replaced by a new glucose sensor within a predetermined time interval; if the determining step is true, setting a tuning factor (R) for a model predictive controller in the microcontroller as a conservative setting otherwise if the determining step is false, maintaining a current tuning factor (R) for the controller; calculating an insulin amount for delivery by the microcontroller based on a model predictive controller that utilizes the tuning factor (R) so as to provide a calculated insulin amount to be delivered to the subject for one or more of the discrete time intervals; and delivering via actuation of a pump by the microcontroller of the insulin amount determined from the calculating step.

In yet another aspect, a system for management of diabetes is provided that includes an episodic glucose meter, continuous glucose meter, and an infusion pump coupled to a controller. The episodic glucose meter is configured to measure blood glucose of a subject at discrete non-uniform time intervals and provide such episodic blood glucose level as a calibration. The continuous glucose monitor is configured to continuously measure glucose level of the subject at discrete generally uniform time intervals and provide the glucose level at each interval in the form of glucose measurement data. The insulin infusion pump to deliver insulin. The microcontroller is in communication with the pump, glucose meter and the glucose monitor. Specifically, the

controller sets a tuning factor (R) to a conservative value for a predetermined time period after the continuous glucose monitor has been replaced with a new continuous glucose monitor such that controller determines an insulin delivery rate for each time interval in the time interval index (k) from the model predictive control based on the conservative tuning factor and commands the pump to deliver at the determined insulin delivery rate.

In each of the above aspects, the following features may also be utilized in combination with each of the aspects. For example, the at least one glucose sensor may include both a continuous glucose sensor and an episodic glucose meter; the conservative tuning factor (R) may include a value of about 500 and the predetermined time period may include about 24 hours from a replacement of the glucose sensor with a new glucose sensor; the aggressive tuning factor (R) may include a value of about 10; the aggressive tuning factor (R) may include a value of about 1000; the model predictive controller has an error weighing factor (Q) that is related to the tuning factor (R) where:

$$10 \leq \frac{R}{Q} \leq 1000$$

Where R may include the tuning factor;

Q may include an error weighing factor.

These and other embodiments, features and advantages will become apparent to those skilled in the art when taken with reference to the following more detailed description of various exemplary embodiments of the invention in conjunction with the accompanying drawings that are first briefly described.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated herein and constitute part of this specification, illustrate presently preferred embodiments of the invention, and, together with the general description given above and the detailed description given below, serve to explain features of the invention (wherein like numerals represent like elements).

FIG. 1 illustrates the system in which a controller for the pump or glucose monitor(s) is separate from both the infusion pump and the glucose monitor(s) and in which a network can be coupled to the controller to provide near real-time monitoring.

FIG. 2A illustrates an exemplary embodiment of the diabetic management system in schematic form.

FIG. 2B illustrates a plot of glucose value for a time interval of 48 hours (or in term of k=12 for each hour of CGM signal) in which other events such as missing CGM data, sensor replacement, or calibration measurements are superimposed on the glucose value plot.

FIG. 2C illustrates the tuning factor for a time interval of 48 hours (or in term of k=12 time interval or index for each hour of CGM signal) in which the tuning factor R is varied due to missing CGM data, sensor replacement, and calibration measurement.

FIG. 3 illustrates the logic utilized in the controller of FIG. 1 or FIG. 2A.

MODES FOR CARRYING OUT THE INVENTION

The following detailed description should be read with reference to the drawings, in which like elements in different

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drawings are identically numbered. The drawings, which are not necessarily to scale, depict selected embodiments and are not intended to limit the scope of the invention. The detailed description illustrates by way of example, not by way of limitation, the principles of the invention. This description will clearly enable one skilled in the art to make and use the invention, and describes several embodiments, adaptations, variations, alternatives and uses of the invention, including what is presently believed to be the best mode of carrying out the invention.

As used herein, the terms “about” or “approximately” for any numerical values or ranges indicate a suitable dimensional tolerance that allows the part or collection of components to function for its intended purpose as described herein. In addition, as used herein, the terms “patient,” “host,” “user,” and “subject” refer to any human or animal subject and are not intended to limit the systems or methods to human use, although use of the subject invention in a human patient represents a preferred embodiment. Furthermore, the term “user” includes not only the patient using a drug infusion device but also the caretakers (e.g., parent or guardian, nursing staff or home care employee). The term “drug” may include hormone, biologically active materials, pharmaceuticals or other chemicals that cause a biological response (e.g., glycemic response) in the body of a user or patient.

FIG. 1 illustrates a drug delivery system 100 according to an exemplary embodiment that utilizes the principles of the invention. Drug delivery system 100 includes a drug delivery device 102 and a remote controller 104. Drug delivery device 102 is connected to an infusion set 106 via flexible tubing 108.

Drug delivery device 102 is configured to transmit and receive data to and from remote controller 104 by, for example, radio frequency communication 112. Drug delivery device 102 may also function as a stand-alone device with its own built in microcontroller. In one embodiment, drug delivery device 102 is an insulin infusion device and remote controller 104 is a hand-held portable controller. In such an embodiment, data transmitted from drug delivery device 102 to remote controller 104 may include information such as, for example, insulin delivery data, blood glucose information, basal, bolus, insulin to carbohydrates ratio or insulin sensitivity factor, to name a few. The microcontroller 104 is configured to include an MPC controller 10 that has been programmed to receive continuous glucose readings from a CGM sensor 112. Data transmitted from remote microcontroller 104 to insulin delivery device 102 may include glucose test results and a food database to allow the drug delivery device 102 to calculate the amount of insulin to be delivered by drug delivery device 102. Alternatively, the remote microcontroller 104 may perform basal dosing or bolus calculation and send the results of such calculations to the drug delivery device. In an alternative embodiment, an episodic blood glucose meter 114 may be used alone or in conjunction with the CGM sensor 112 to provide data to either or both of the microcontroller 104 and drug delivery device 102. Alternatively, the remote microcontroller 104 may be combined with the meter 114 into either (a) an integrated monolithic device; or (b) two separable devices that are dockable with each other to form an integrated device. Each of the devices 102, 104, and 114 has a suitable microcontroller (not shown for brevity) programmed to carry out various functionalities.

Drug delivery device 102 may also be configured for bi-directional wireless communication with a remote health monitoring station 116 through, for example, a wireless

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communication network 118. Remote controller 104 and remote monitoring station 116 may be configured for bi-directional wired communication through, for example, a telephone land based communication network. Remote monitoring station 116 may be used, for example, to download upgraded software to drug delivery device 102 and to process information from drug delivery device 102. Examples of remote monitoring station 116 may include, but are not limited to, a personal or networked computer 126, server 128 to a memory storage, a personal digital assistant, other mobile telephone, a hospital base monitoring station or a dedicated remote clinical monitoring station.

Drug delivery device 102 includes electronic signal processing components including a central processing unit and memory elements for storing control programs and operation data, a radio frequency module 116 for sending and receiving communication signals (i.e., messages) to/from remote controller 104, a display for providing operational information to the user, a plurality of navigational buttons for the user to input information, a battery for providing power to the system, an alarm (e.g., visual, auditory or tactile) for providing feedback to the user, a vibrator for providing feedback to the user, a drug delivery mechanism (e.g. a drug pump and drive mechanism) for forcing a insulin from a insulin reservoir (e.g., a insulin cartridge) through a side port connected to an infusion set 108/106 and into the body of the user. An example of a drug delivery device 102 (or pump 16) can be in the form of a modified Animas Vibe insulin pump manufactured by Animas Corporation in Wayne, Pa. USA.

Glucose levels or concentrations can be determined by the use of the CGM sensor 112. The CGM sensor 112 utilizes amperometric electrochemical sensor technology to measure glucose with three electrodes operably connected to the sensor electronics and are covered by a sensing membrane and a biointerface membrane, which are attached by a clip.

The top ends of the electrodes are in contact with an electrolyte phase (not shown), which is a free-flowing fluid phase disposed between the sensing membrane and the electrodes. The sensing membrane may include an enzyme, e.g., glucose oxidase, which covers the electrolyte phase. In this exemplary sensor, the counter electrode is provided to balance the current generated by the species being measured at the working electrode. In the case of a glucose oxidase based glucose sensor, the species being measured at the working electrode is H_2O_2 . The current that is produced at the working electrode (and flows through the circuitry to the counter electrode) is proportional to the diffusional flux of H_2O_2 generated by this electrochemical transformation of glucose into its enzymatic byproducts. Accordingly, a raw signal may be produced that is representative of the concentration of glucose in the user's body, and therefore may be utilized to estimate a meaningful glucose value. Details of the sensor and associated components are shown and described in U.S. Pat. No. 7,276,029, which is incorporated by reference herein as if fully set forth herein this application. In one embodiment, a continuous glucose sensor from the Dexcom Seven System® (manufactured by Dexcom Inc.) can also be utilized with the exemplary embodiments described herein.

In one embodiment of the invention, the following components can also be utilized as a system for management of diabetes that is akin to an artificial pancreas: OneTouch Ping® Glucose Management System by Animas Corporation that includes at least an infusion pump and an episodic glucose sensor; and DexCom® G4 Platinum® CGM by DexCom Corporation with interface to connect these com-

ponents and programmed in MATLAB® language and accessory hardware to connect the components together; and control algorithms in the form of an MPC that automatically regulates the rate of insulin delivery based on the glucose level of the patient, historical glucose measurement and anticipated future glucose trends, and patient specific information.

FIG. 2A illustrates a schematic diagram 200 of the system 100 in FIG. 1 programmed with the solution devised by applicants to counteract a less than desirable effect of a closed-loop control system. In particular, FIG. 2A provides for an MPC programmed into a control logic module 10 that is utilized in controller 104. MPC logic module 10 receives a desired glucose concentration or range of glucose concentration 12 (along with any modification from an update filter 28 so that it is able to maintain the output (i.e., glucose level) of the subject within the desired range of glucose levels.

Referring to FIG. 2A, the first output 14 of the MPC-enabled control logic 10 can be a control signal to an insulin pump 16 to deliver a desired quantity of insulin 18 into a subject 20 at predetermined time intervals, which can be indexed every 5 minutes using time interval index k. A second output in the form of a predicted glucose value 15 can be utilized in control junction B. A glucose sensor 22 (or 112 in FIG. 1) measures the glucose levels in the subject 20 in order to provide signals 24 representative of the actual or measured glucose levels to control junction B, which takes the difference between measured glucose concentration 24 and the MPC predictions of that measured glucose concentration. This difference provides input for the update filter 26 of state variables of the model. The difference 26 is provided to an estimator (also known as an update filter 28) that provides for estimate of state variables of the model that cannot be measured directly. The update filter 28 is preferably a recursive filter in the form of a Kalman filter with tuning parameters for the model. The output of the update or recursive filter 28 is provided to control junction A whose output is utilized by the MPC in the control logic 10 to further refine the control signal 14 to the pump 16 (or 102 in FIG. 1). A tuning factor 34 is used with the MPC controller 10 to “tune” the controller in its delivery of the insulin. To accomplish this, applicants have devised the use of a calibration index module 30 and data omission module 32 to adjust the tuning factor. Calibration index module 30 is configured to track the number of glucose measurement calibration, which is typically accomplished by an episodic glucose monitor, such as, for example, a blood glucose test strip and meter system. Data omission index module 32 is configured to track the number of missing measurements or data from the continuous glucose monitor 22.

A brief overview of the MPC noted above that is used in control logic 10 is warranted here. The MPC logic is formulated to control a subject glucose level to a safe glucose zone, with the lower blood glucose limit of the zone varying between 80-100 mg/dL and the upper blood glucose limit varying between about 140-180 mg/dL; the algorithm will henceforth be referred to as the “zone MPC”. Controlling to a target zone is, in general, applied to controlled systems that lack a specific set point with the controller’s goal being to keep the controlled variable, (CV), for example the glucose values, in a predefined zone. Control to zone (i.e., a normoglycemic zone) is highly suitable for the artificial pancreas because of the absence of a natural glycemic set point. Moreover, an inherent benefit of control to zone is the ability to limit pump actuation/activity in a way that if glucose levels are within the zone then no extra correction shall be suggested.

In real-time, the insulin delivery rate I_D from the zone MPC law is calculated by an on-line optimization, which evaluates at each sampling time the next insulin delivery rate. The optimization at each sampling time is based on the estimated metabolic state (plasma glucose, subcutaneous insulin) obtained from the dynamic model stored in module 10.

The MPC of control logic 10 incorporates an explicit model of human T1DM glucose-insulin dynamics. The model is used to predict future glucose values and to calculate future controller moves that will bring the glucose profile to the desired range. MPC in controllers can be formulated for both discrete- and continuous-time systems; the controller is set in discrete time, with the discrete time (stage) index k referring to the epoch of the k^{th} sample occurring at continuous time $t=k \cdot T_s$, where $T_s=5$ min is the sampling period. Software constraints ensure that insulin delivery rates are constrained between minimum (i.e., zero) and maximum values. The first insulin infusion (out of N steps) is then implemented. At the next time step, k+1 based on the new measured glucose value and the last insulin rate, the process is repeated.

Specifically, we start with the original linear difference model used for zone MPC:

$$G'(k)=a_1G'(k-1)+a_2G'(k-2)+a_3G'(k-3)+a_4G'(k-4)+a_5G'(k-5)+bI_M(k-4)+c_1I_D(k-1)+c_2I_D(k-2)+d_1I_D'(k-1)+d_2I_D'(k-2) \quad \text{Eq. (1)}$$

where:

k is the discrete time interval index having a series of indexing counters where $k=1, 2, 3 \dots$

G' is the measured glucose concentration

I_M is the “mapped insulin” which is not a measured quantity

I_D' is the delivered insulin or a manipulated variable

and coefficients $a_1 \sim 2.993$; $a_2 \sim (-3.775)$; $a_3 \sim 2.568$; $a_4 \sim (-0.886)$; $a_5 \sim 0.09776$; $b \sim (-1.5)$; $c_1 \sim 1.665$; $c_2 \sim (-0.693)$; $d_1 \sim 0.01476$; $d_2 \sim 0.01306$.

Using the FDA accepted metabolic simulator known to those skilled in the art, Eq. (1) can be reduced to the following linear difference model in Equation (2):

$$(a) \quad G'(k) = 2.993G'(k-1) - 3.775G'(k-2) + 2.568G'(k-3) - 0.886G'(k-4) + 0.09776G'(k-5) - 1.5I_M(k-4) + 0.1401\text{Meal}_M(k-2) + 1.933\text{Meal}_M(k-3) \quad (2)$$

$$(b) \quad I_M(k) = 1.665I_M(k-1) - 0.693I_M(k-2) + 0.01476I_D'(k-1) + 0.01306I_D'(k-2)$$

$$(c) \quad \text{Meal}_M(k) = 1.501\text{Meal}_M(k-1) + 0.5427\text{Meal}_M(k-2) + 0.02279\text{Meal}(k-1) + 0.01859\text{Meal}(k-2)$$

where:

G' is the glucose concentration output (G) deviation variable (mg/dL), i.e. $G'=G-110$ mg/dL,

I_D' is the insulin infusion rate input (I_D) deviation variable (U/h), i.e. $I_D' = I_D - \text{basal U/h}$,

Meal is the CHO ingestion input (gram-CHO),

I_M is the mapped subcutaneous insulin infusion rates (U/h), and

Meal_M is the mapped CHO ingestion input (gram-CHO).

The dynamic model in Eq. (2) relates the effects of insulin infusion rate (I_D), and CHO ingestion input (Meal) on plasma glucose. The model represents a single average model for the total population of subjects. The model and its parameters are fixed.

The second-order input transfer functions described by parts (b) and (c) in Eq. (2) are used to generate an artificial input memory in the zone MPC schema to prevent insulin over-dosing, and consequently prevent hypoglycemia. In order to avoid over-delivery of insulin, the evaluation of any sequential insulin delivery must take into consideration the past administered insulin against the length of the insulin action. However, a one-state linear difference model with a relatively low order uses the output (glycemia) as the main source of past administered input (insulin) “memory.” In the face of the model mismatch, noise, or change in the subject’s insulin sensitivity, this may result in under- or over-delivery of insulin. This is mitigated by adding two additional states (I_M and $Meal_M$) for the mapped insulin and meal inputs that carry a longer insulin memory.

Zone MPC is applied when the specific set point value of a controlled variable (CV) is of low relevance compared to a zone that is defined by upper and lower boundaries. Moreover, in the presence of noise and model mismatch there is no practical value using a fixed set point. Zone MPC was developed through research by the University of California at Santa Barbara and the Sansum Diabetes Research Institute. Other details of the derivation for the Zone MPC technique are shown and described in Benjamin Grosman, PhD., Eyal Dassau, PhD., Howard C. Zisser, M.D., Lois Jovanović, M.D., and Francis J. Doyle III, PhD. “Zone Model Predictive Control: A Strategy to Minimize Hyper and Hypoglycemic Events” Journal of Diabetes Science and Technology, Vol. 4, Issue 4, July 2010, and US Patent Application Publication No. 2011/0208156 to Doyle et al., entitled “Systems, Devices, and Methods to Deliver Biological Factors or Drugs to a Subject,” with the publication date of Aug. 25, 2011, all which are incorporated by reference as if set forth herein with a copy in the Appendix. Additional details of the Zone MPC are shown and described in US Patent Application Publication No. 20110208156, which is incorporated by reference as if set forth herein with a copy in the Appendix. A related derivation of zone MPC was presented in Maciejowski J M., “PREDICTIVE CONTROL WITH CONSTRAINTS” Harlow, UK: Prentice-Hall, Pearson Education Limited, 2002. The zone MPC is implemented by defining fixed upper and lower bounds as soft constraints by letting the optimization weights switch between zero and some final values when the predicted CVs are in or out of the desired zone, respectively. The predicted residuals are generally defined as the difference between the CV that is out of the desired zone and the nearest bound. Zone MPC is typically divided into three different zones. The permitted range is the control target and it is defined by upper and lower bounds. The upper zone represents undesirable high predicted glycemic values. The lower zone represents undesirable low predicted glycemic values that represent hypoglycemic zone or a pre-hypoglycemic protective area that is a low alarm zone. The zone MPC optimizes the predicted glycemia by manipulating the near-future insulin control moves to stay in the permitted zone under specified constraints.

The core of zone MPC lies in its cost function formulation that holds the zone formulation. Zone MPC, like any other forms of MPC, predicts the future output by an explicit model using past input/output records and future input moves that need to be optimized. However, instead of driving to a specific fixed set point, the optimization attempts to keep or move the predicted outputs into a zone that is defined by upper and lower bounds. Using a linear difference model, the glycemic dynamics are predicted and

the optimization reduces future glycemic excursions from the zone under constraints and weights defined in its cost function.

The zone MPC cost function J used in the presented work is defined as follows:

$$J(I_D') = Q \cdot \sum_{j=1}^P \|G^{zone}(k+j)\| + R \cdot \sum_{j=0}^{M-1} \|I_D'(k+j)\| \quad (3)$$

s.t.

$$G(k+j) = f[G(k+j-1), I_D'(k+j-1)] \quad \forall j = 1, P$$

$$-basal(k+j) \leq I_D'(k+j) \leq 72 \quad \forall j = 0, M-1$$

or for our applications:

$$J(I_D') = \sum \|G^{zone}(k+j)\| + R \cdot \sum \|I_D'(k+j) - basal(k+j)\| \quad (4)$$

where

J is a cost function;

Q is a weighting factor on the predicted glucose term;

R is a tuning factor on the future proposed inputs in the cost function;

f is the prediction function (in Eq. (2)); and

vector I_D contains the set of proposed near-future insulin infusion amounts. It is the “manipulated variable” because it is manipulated in order to find the minimum in J.

G^{zone} is a variable quantifying the deviation of future model-predicted CGM values G outside a specified glycemic zone, and is determined by making the following comparisons:

$$G^{zone} = \begin{cases} 0 & \text{if } G_{ZL} \leq G \leq G_{ZH} \\ G - G_{ZH} & \text{if } G > G_{ZH} \\ G_{ZL} - G & \text{if } G < G_{ZL} \end{cases} \quad (5)$$

where the glycemic zone is defined by the upper limit G_{ZH} and the lower limit G_{ZL} .

Thus, if all the predicted glucose values are within the zone, then every element of G^{zone} is equal to 0, and consequently J is minimized with $I_D = \text{basal}$ for that time of day, i.e., the algorithm “defaults” to the patient’s current basal insulin infusion rate. On the other hand, if any of the predicted glucose values are outside the zone, then $G^{zone} > 0$ and thus “contribute” to the cost function. In this case, the near-future proposed insulin infusion amounts I_D will deviate from the basal in order to prevent out-of-zone deviation in G^{zone} from ever happening, which will also “contribute” to the cost function. Then, a quantitative balance is found in the optimization, based on the weighting factor R.

In order to solve optimization problem of Equations (2)-(5), commercially available software (e.g., MATLAB’s “fmincon.m” function) is utilized. For this function, the following parameters are used for each optimization:

Initial guess for the insulin delivery rates, $I_D'(0)$, is the

null vector $\vec{0} \in \mathbb{R}^M$, e.g., if $M=5$ the initial guess for each optimization is $I_D' = [0 \ 0 \ 0 \ 0 \ 0]$. This implies that the initial guess is equivalent to the basal rate.

Maximum number of function evaluations allowed is $\text{Max}_f = 100 \cdot M$, where M is control horizon as described earlier.

Maximum number of iterations is $\text{Max}_i = 400$, which is fixed.

Termination on the cost function values $\text{Term cost} = 1e-6$, which is fixed.

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Termination tolerance Term_tol on the manipulated variables I_D' is 1e-6.

The following hard constraints are implemented on the manipulated variables (I_D'):

$$-\text{basal} \leq I_D' \leq 72 \text{ U/h} \quad (6)$$

where basal is the subject's basal rate as set by the subject or his/her physician, expected in the range of about 0.6 to about 1.8 U/hr.

Although the values of control horizon parameter M and prediction horizon parameter P have significant effects on the controller performance, and are normally used to tune an MPC based controller, they can be heuristically tuned based on knowledge of the system. Tuning rules are known to those skilled in the field. According to these rules, M and P may vary between:

$$\begin{aligned} 2 \leq M \leq 10 \\ 20 \leq P \leq 120 \end{aligned} \quad (7)$$

In the preferred embodiments, we use the nominal values of M=5 and P=108.

The ratio of the output error weighting factor Q and the input change weighting matrix or tuning factor R may vary between:

$$10 \leq \frac{R}{Q} \leq 1000 \quad (8)$$

In the preferred embodiments, we may use the nominal value of R/Q=500.

Once the controller **10** is initialized and switched on in the microcontroller in device **102** or **104**, real-time calculations take place every five minutes, corresponding to the sample time for the glucose sensor **22**. The first element of I_D is delivered as an insulin dose to the patient through the insulin pump **16**, five minutes elapse, a new CGM reading becomes available, and the process repeats. It is noted that the future control moves are hard-constrained, set by the insulin pump's ability to deliver a maximum rate of insulin and the inability to deliver negative insulin values. Other details of related subject matter including state estimator, and other MPC are provided by Rachel Gillis et al., "Glucose Estimation and Prediction through Meal Responses Using Ambulatory Subject Data for Advisory Mode Model Predictive Control" Journal of Diabetes Science and Technology Vol. 1, Issue 6, November 2007 and by Youqing Wang et al., "Closed-Loop Control of Artificial Pancreatic β -Cell in Type 1 Diabetes Mellitus Using Model Predictive Iterative Learning Control" IEEE Transactions on Biomedical Engineering, Vol. 57, No. 2, February 2010, which are hereby incorporated by reference into this application as if fully set forth herein.

It is known that the tuning parameter or tuning factor (designated here as "R") can have a significant effect on the quality of the glucose control. The parameter—known as the aggressiveness factor, gain, among other names—determines the speed of response of the algorithm to changes in glucose concentration. A relatively conservative value of R results in a controller that is slow to adjust insulin infusion amounts (relative to basal) in response to changes in glucose; on the other hand, a relatively aggressive value of R results in a controller that is quick to respond to changes in glucose. In principle, an aggressive controller would result in the best glucose control if 1) the available glucose measurements are accurate, and moreover 2) the model

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predictions of future glucose trends are accurate. If these conditions are not true, then it may be safer to use a conservative controller.

A discussion of the tuning factor R (referenced here as **34**) in FIG. 2A is worthwhile at this point. As it is not straightforward to determine either the accuracy of the glucose measurements on-line or the accuracy of the model predictions, it can be difficult to know the appropriate tuning factor **34** or R to use for the current conditions. However, in specific circumstances, it is possible to ascertain with a high degree of certainty when a continuous glucose monitor (CGM) has become "less accurate" or "more accurate" in a qualitative sense.

Applicants believe that it is reasonable to assume that a CGM may become less accurate with each sample following a calibration, and has suddenly become less accurate when it fails to report a glucose measurement. Missed or omitted CGM measurements may be due to uncertainty in the glucose trend (a CGM algorithm feature) or simply to radio frequency communication issues. Similarly, it is reasonable to assume that the CGM has become more accurate following a calibration, and following a reestablishment of reporting glucose values after one or more missed readings.

Applicants have discovered therefore that it is possible to use these insights to tune the controller automatically, i.e., use a more conservative value of R for the tuning factor when the CGM has become less accurate, and a more aggressive value when the CGM has become more accurate. This is demonstrated, in a general sense, below.

Let the aggressiveness or tuning factor, R, be bounded by the constants Rmin (for the most aggressive controller) and Rmax (for the most conservative controller):

$$R_{\min} \leq R \leq R_{\max} \quad \text{Eq. (9)}$$

Let there be two nominal increments, strictly positive quantities: r_1 , a relatively small increment associated with the accuracy of a CGM in relation to how recent a calibration was, and r_2 , a larger increment associated with the accuracy of a CGM as it pertains to missed samples.

The tuning factor to be used in the MPC calculation for the current sampling instant, indexed by k, is R(k), where R(k) is automatically updated at each sample based on a nominal R value, R_{NOM} , which could in general be different for each user:

$$R(k) = R_{\text{NOM}} + r_1 * \text{CAL}(k) + r_2 * \text{MISSED}(k), \quad \text{Eq. (10)}$$

$$\text{and } R_{\min} \leq R(k) \leq R_{\max} \quad \text{Eq. (11)}$$

$$\text{CAL}(k) = k - k_{\text{CAL}} - 6 \text{ for } k - k_{\text{CAL}} \geq 6 \quad \text{Eq. (12)}$$

$$\text{CAL}(k) = k - k_{\text{CAL}} - 6 \text{ for } k - k_{\text{CAL}} < 6 \quad \text{Eq. (13)}$$

where:

$$\begin{aligned} R_{\text{NOM}} \leq R_{\max} \leq 100 * R_{\text{NOM}} \\ R_{\text{NOM}} / 100 \leq R_{\min} \leq R_{\text{NOM}} \\ (R_{\max} - R_{\min}) / 500 \leq r_1 \leq (R_{\max} - R_{\min}) / 50 \\ (R_{\max} - R_{\min}) / 50 \leq r_2 \leq (R_{\max} - R_{\min}) / 5 \end{aligned}$$

CAL(k) is the calibration index. It is noted that R_{NOM} can be a value from about zero to about 1000 (e.g., $0 \leq R_{\text{NOM}} \leq 1000$); although it should be noted that this value and range are dependent on the specific cost function in the particular model being used and one skilled in the art would be able to configure the appropriate range for R_{NOM} , depending on the model being used. In the exemplary embodiments, r_1 can be any number from about 1 to about 50 and r_2 can be any number from about 10 to about 1000 and preferably about 500. Although the tuning factor has been provided as a range of specific numerical

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values for the embodiments described herein, we note that each system would use different configurations of the tuning factor to control the desired response of the controller (and pump) in delivering the insulin. Hence, it is our intent not to be bound to any specific numerical value and therefore, as described herein, the tuning factor may include any value from a first value or interval that will cause the pump to have a very quick (or highly aggressive) response in delivering the insulin to a second value or interval that will cause the pump to have very slow (or conservative) response in delivering insulin.

The current sample index is “k” where k_{CAL} is the sample index of the most recent CGM calibration with a suitable referential glucose analyzer or glucose meter 114, and k_{CAL2} is the sample index of the second-most recent CGM calibration with a referential glucose meter 114. Thus, 30 min (e.g., 6 samples) following a calibration with the referential glucose meter 114, calibration index module 32 or CAL(k) is zero. Thereafter, CAL grows by one at each sample until the 30 min after the next calibration. This correction to the tuning factor R of module 34 at instance “k” (i.e., R(k)) results in a slightly more conservative controller (i.e., higher value of R for Equation (4)) with every consecutive CGM measurement by sensor 112 for each time interval index k, until the next calibration. The 30 minute buffer immediately following a calibration, during which the control logic 10 will act relatively conservatively, is due to potentially significant “jumps” in CGM values immediately following calibrations.

Additional details of how the tuning factor R is adjusted for certain events (e.g., signal dropouts or calibration) can be seen in U.S. patent application Ser. No. 13/708,032 filed on Dec. 7, 2012, which is hereby incorporated by reference into this application in its entirety herein.

Besides the adjustment of the tuning factor for CGM signal drops or calibrations, we have also devised a strategy to deal with the inaccuracy of CGM sensor whenever such sensor is initially installed (or replaced with another one) on the skin of the user.

To recap, the system of FIG. 2A is provided to manage diabetes of a subject. In this system, the following components are utilized: an episodic glucose meter 29, continuous glucose sensor 22, pump 16, and controller 10. The meter 29 measures blood glucose of a subject at discrete non-uniform time intervals (e.g., every 4 hours) and provide such episodic blood glucose level as a calibration index 30 for each interval in a time interval index (k where a time interval between k and k+1 is about 5 minutes). The continuous glucose monitor continuously measure glucose level of the subject at discrete generally uniform time intervals (e.g., approximately every 30 seconds or every minute) and provide the glucose level at each interval in the form of glucose measurement data, in which any omission of a glucose measurement in any interval is stored in an omission index 32. The insulin infusion pump is controlled by the controller 10 to deliver insulin to the subject 20. As used herein, the term “insulin” is not limited to the peptide hormone extracted from animals or genetically engineered insulin, biosynthetic recombinant human insulin, or its analogues but may include other drugs or biologics designed to mimic insulin or other materials having similar effects of insulin on the human body. The controller 10 is programmed with the appropriate MPC program to control the pump and communicate with the glucose meter and the glucose monitor. In this aspect, the controller determines a tuning factor 34 based on (a) a calibration index 30 derived from episodic blood glucose measurements and (b) an omission index 32

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for the MPC 10 such that controller determines an insulin delivery rate for each time interval in the time interval index (k) from the model predictive control based on (1) desired glucose concentration 12, (2) glucose concentration 24 measured by the monitor 22 at each interval of the interval index (k), and (3) the tuning factor 34. However, we have devised the system so that when there is a change or replacement of the CGM sensor (which sensor replacement can be detected by the pump or confirmed by the user via a switch), the system sets the tuning factor R to a conservative value such as, for example, 500, for a predetermined time period such as, for example, 8 hours, 12 hours, 24 hours or longer or shorter as appropriate for the inherent inaccuracy of the particular CGM sensor being used.

With reference to FIGS. 2B and 2C, telemetry outputs of the system are provided to demonstrate operation of this system. In FIG. 2B, CGM output signal are shown over 48 hours whereas an output of the tuning factor over the same time frame in FIG. 2C is juxtaposed below FIG. 2B. At event “a” in FIG. 2B, a calibration is made which means that, in a qualitative sense, the output signal from the CGM sensor can be viewed as being more accurate (because of the calibration with the episodic glucose sensor or test strip). Hence, at “b” in FIG. 2C, the MPC (in the microcontroller) can increase the aggressiveness of the tuning factor R (reducing its numerical value to 50) and slowly ramping the aggressiveness of the factor R higher in the next two hours (from 12 hours to 14 hours). At event “c” in FIG. 2B, the microcontroller detects from a flag or switch 36 (or the user can confirm) that the CGM sensor has been changed to a new CGM sensor. The microcontroller, as programmed with an embodiment of our invention, immediately switches the tuning factor to a more conservative tuning factor so that the dosing of insulin is more conservative. And for a predetermined time period, from 14 hours to about 40 hours, this more conservative tuning factor is maintained for a predetermined time (e.g., from 14 hours to about 40 hours) regardless of dropped signals from the new CGM sensor. As used herein, the phrase “conservative tuning factor” indicates a tuning factor R for the controller that is intended to ensure that the insulin dosing delivery rate (relative to basal in response to changes in glucose for the intended application) that is slow enough and within the constraints in the particular application of the system to meet the safety or regulatory requirements for such application. As a non-limiting example, the conservative tuning factor can be any value from about 500 to 1000. But it should be clear that this tuning factor can be any number that is used to affect the response or “gain” of the particular configuration of a system utilizing a closed-loop controller (feedback, feedforward or hybrid controller) as long as such tuning factor is considered to be safe or conservative by those skilled in the art.

By virtue of the disclosure provided herein, applicants have also devised a method to control an infusion pump to control an infusion pump with a controller to control the pump and receive data from at least one glucose sensor. With reference to FIG. 3, exemplary method will now be described. The method starts by measuring in step 302 a glucose level in the subject from the glucose sensor (22 or 29) to provide at least one glucose measurement for each time interval in a series of discrete time interval index (“k”). At step 304, the system queries as to whether a CGM sensor change has been made within a predetermined time period X. A determination of a sensor change in 304 can be obtained by the microcontroller checking a sensor change log, sensor change flag, or by a combinations of one or more

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signals indicative of a sensor change (e.g., a user manually actuated signal). If this query returns a “true” or a “yes”, the system checks at step 306 if a countdown timer for predetermined time X is equal to zero (or a count-up timer being equal to the predetermined time X). If not true (i.e., a “no”), the system moves to step 308 where the tuning factor is set to a conservative value. At step 312, the MPC in the microcontroller now determines the appropriate insulin dosing I_D (from Equations 2-5) within the zone taking into account the cost J, which is affected by the tuning factor R. At step 314, the microcontroller actuates the pump motor in the pump 102 to deliver the appropriate insulin dose calculated in step 312. At step 316, the microcontroller returns to the main routine.

On the other hand, if the query at step 304 returns a false (i.e., a “no”), the system maintains the tuning factor as currently set prior to the sensor change event. Alternatively, the system can still calculate the appropriate tuning factor for the work load as described earlier in relation to Equations 9-13.

While the invention has been described in terms of particular variations and illustrative figures, those of ordinary skill in the art will recognize that the invention is not limited to the variations or figures described. For example, the closed-loop controller need not be an MPC controller but can be, with appropriate modifications by those skilled in the art, a PID controller, a PID controller with internal model control (IMC), a model-algorithmic-control (MAC) that are discussed by Percival et al., in “Closed-Loop Control and Advisory Mode Evaluation of an Artificial Pancreatic β Cell: Use of Proportional-Integral-Derivative Equivalent Model-Based Controllers” Journal of Diabetes Science and Technology, Vol. 2, Issue 4, July 2008. In addition, where methods and steps described above indicate certain events occurring in certain order, those of ordinary skill in the art will recognize that the ordering of certain steps may be modified and that such modifications are in accordance with the variations of the invention. Additionally, certain of the steps may be performed concurrently in a parallel process when possible, as well as performed sequentially as described above. Therefore, to the extent there are variations of the invention, which are within the spirit of the disclosure or equivalent to the inventions found in the claims, it is the intent that this patent will cover those variations as well.

What is claimed is:

1. A method to control a system for management of diabetes using a model predictive controller having a tuning factor (R), the tuning factor (R) being adjustable between a conservative tuning factor and an aggressive tuning factor, the system comprising an infusion pump with a microcontroller to control the pump and receive data from at least one glucose sensor, and the method comprising:
 - measuring glucose level in the subject from the glucose sensor to provide at least one glucose measurement in each time interval in a series of discrete time intervals;
 - determining a change in an accuracy of the system, the determining comprising:
 - determining a reduction in the accuracy of the system responsive to the glucose sensor being replaced by a new glucose sensor within a predetermined time interval; and
 - determining an increase in the accuracy of the system responsive to a calibration of the glucose sensor;
 - setting the tuning factor (R) for the model predictive controller in the microcontroller as the conservative tuning factor responsive to determining the reduction in

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the accuracy of the system, or the aggressive tuning factor responsive to determining the increase in the accuracy of the system;

- calculating an insulin amount for delivery by the microcontroller based on the model predictive controller that utilizes the tuning factor (R) so as to provide a calculated insulin amount to be delivered to the subject for one or more of the discrete time intervals; and
- delivering via actuation of a pump by the microcontroller of the insulin amount determined from the calculating step.

2. The method of claim 1, in which the conservative tuning factor (R) comprises a value of about 500 and the predetermined time period comprises about 24 hours from a replacement of the glucose sensor with a new glucose sensor.

3. The method of claim 2, in which the tuning factor (R) comprises a value of about 10.

4. The method of claim 1, in which the tuning factor (R) comprises a value of about 1000.

5. The method of claim 1, in which the conservative setting of the tuning factor comprises a value of about 500.

6. The method of claim 1, in which tuning factor comprises any value from a first value that will cause the pump to have a quicker response in delivering the insulin to a second or conservative value that will cause the pump to have a slower response in delivering insulin and the conservative setting comprises the conservative value of the tuning factor.

7. The method of claim 1, in which the model predictive controller has an error weighing factor (Q) that is related to the tuning factor (R) where:

$$10 \leq \frac{R}{Q} \leq 1000$$

Where R comprises the tuning factor;

Q comprises an error weighing factor.

8. The method of claim 1, in which the at least one glucose sensor comprises a continuous glucose sensor and an episodic glucose meter.

9. A system for management of diabetes comprising:

- an episodic glucose meter to measure blood glucose of a subject at discrete non-uniform time intervals and provide such episodic blood glucose level as a calibration;
- a continuous glucose monitor to continuously measure glucose level of the subject at discrete generally uniform time intervals and provide the glucose level at each interval in the form of glucose measurement data; an insulin infusion pump to deliver insulin;
- a microcontroller using a model predictive controller having a tuning factor (R), the tuning factor (R) being adjustable between a conservative tuning factor and an aggressive tuning factor, the microcontroller being in communication with the pump, glucose meter and the glucose monitor in which the controller sets the tuning factor (R) to the conservative tuning factor for a predetermined time period after the continuous glucose monitor has been replaced with a new continuous glucose monitor, or to an aggressive tuning factor for the predetermined time period after the continuous glucose monitor has been calibrated, such that controller determines an insulin delivery rate for each time interval in the time interval index (k) from the model predictive control based on the tuning factor (R) and

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commands the pump to deliver insulin at the determined insulin delivery rate.

10. The system of claim 9, in which the conservative setting for the tuning factor (R) comprises a value of about 500.

11. The system of claim 9, in which the tuning factor (R) comprises a value of about 10.

12. The system of claim 9, in which the tuning factor (R) comprises a value of about 1000.

13. The system of claim 9, in which the model predictive controller has an error weighing factor (Q) that is related to the tuning factor (R) where:

$$10 \leq \frac{R}{Q} \leq 1000$$

Where R comprises the tuning factor;

Q comprises an error weighing factor.

14. The system of claim 9, in which the tuning factor comprises any value from a first value that will cause the pump to have a quicker response in delivering the insulin to a second or conservative value that will cause the pump to have a slower response in delivering insulin and the conservative setting comprises the conservative value of the tuning factor.

15. A method to control a system for management of diabetes using a model predictive controller having a tuning factor (R), the tuning factor (R) being adjustable between a conservative tuning factor and an aggressive tuning factor, the system comprising an infusion pump with a microcon-

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troller to control the pump and receive data from at least one glucose sensor, and the method comprising:

measuring a glucose level in the subject from the glucose sensor to provide at least one glucose measurement in each time interval in a series of discrete time intervals; determining a change in an accuracy of the system, the determining comprising:

determining a reduction in the accuracy of the system responsive to one or more of the glucose sensor being replaced by a new glucose sensor within a predetermined time interval, an increase in each successive sample following a calibration of the glucose sensor or a failure of the glucose sensor to report a glucose measurement; and

determining an increase in the accuracy of the system responsive to one or more of a calibration of the glucose sensor or a reestablishment of the glucose sensor reporting glucose measurements;

setting the tuning factor (R) for the model predictive controller in the microcontroller as the conservative tuning factor responsive to determining the reduction in the accuracy of the system, or the aggressive tuning factor responsive to determining the increase in the accuracy of the system;

calculating an insulin amount for delivery by the microcontroller based on a model predictive controller that utilizes the tuning factor (R) so as to provide a calculated insulin amount to be delivered to the subject for one or more of the discrete time intervals; and

delivering via actuation of a pump by the microcontroller of the insulin amount determined from the calculating step.

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